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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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ANALYSIS OF THE CRITICAL SHIELDING VOLUME FOR UNDERGROUND SHELTERS

by

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CONTENTS

ILLUSTRATIONS

Figures

Tables

OBJECT OF PROJECT

To carry out a reseach and development program which will furnish methods, procedures, and plans for shelters for use by the Naval Shore Establishment in order to protect personnel and vital equipment and supplies from atomic war attack.

OBJECT OF TASK

To improve existing knowledge of the gamma and neutron shielding properties of shelters.

To verify experimentally, where necessary, theoretical knowldege developed in this field in order to fill in gaps in nuclear shielding knowledge.

OBJECT OF THIS REPORT

This paper is an interim technical note on the over-all subject of the gamma and neutron shielding properties of shelters and a final report on the results of a study to determine the volume of soil above a buried shelter which is important as a shield against nuclear radiation. This volume of soil is here defined as "the critical shielding volume."

ABSTRACT

The development of

The ~~Bureau of Yards and Docks has assigned the U. S. Naval Civil Engineering Laboratory the responsibility of developing~~ design principles for constructing atomic warfare shelters for naval shore establishments ~~is~~ described. Part of this problem is evaluating various shelter systems for protection against nuclear radiation.

This report presents the results of an investigation to determine which part of the earth covering a buried shelter is the most important as a radiation shield. The following equation:

equals

$$(1-F)\ E_1(u_1 x) = E_1(u_1 x \sec \theta)$$

when solved for the critical angle, θ, will define the volume of earth which provides the fraction, F, of the total shielding to the shelter system. E_1 is the exponential integral; u_1 is the effective linear absorption coefficient for the shield material; x is the effective shield thickness.

Computations have been completed for slab and hemisphere geometry for fractions, F, of 0.99 and 0.999. For slab geometry x is equivalent to t_m, the thickness of the slab shield. For hemispherical geometry x is equivalent to R_m which is the sum of the radius of the hemisphere plus the minimum cover over the arch.

In order to preserve the shielding integrity of the shelter system, the shielding volume defined by θ should not be violated by openings of any sort such as vents, ducts, and entranceways.

*Theta

BACKGROUND

The shelter program for the military or shore establishment requires that structures withstand very high nuclear blast pressures. Planning shelters to resist over 100-psi must be considered. Recent tests[1] indicate that only buried shelters and structures can withstand these high pressures. Shelters buried only a few feet have many advantages over surface structures. A buried one is not subject to drag or horizontal blast pressures; the interaction of soil and structure greatly increases the strength of even conventional types of construction;[1] and burial provides protection from thermal and nuclear radiation.

A buried or earth-covered structure depends primarily on its depth of cover for shielding from nuclear radiation. For radiation originating in the air above the shelter position, the earth shield directly between the shelter and the source of radiation is the most important. The earth directly over or adjacent to the structure itself then provides the primary shielding.

THE PROBLEM

The determination of the required volume of soil above a buried shelter as a shield against nuclear radiation is the concern of the present study. Knowing the location of the shelter with respect to the expected location of ground zero and the size of the nuclear weapon, it is possible to predict within an order of magnitude the amount of nuclear radiation to be expected.[2] Given a maximum limit to the total allowable dose within the shelter, it is possible to determine the reduction factor which the nuclear shielding must provide. It is then possible to determine the amount of earth or other material that must be used to provide this degree of protection.[3,4]

If this amount of shielding material could be placed around the entire structure, the problem of nuclear shielding would be simple. Unfortunately, this idealized shield must be violated by providing entranceways, ventilation ducts, and other utilities. The design of the nuclear shield and these accesses to the shelter should still provide the required attenuation of nuclear radiation.

Referring to Figure 1, it can be seen that a buried shelter is shielded from nuclear radiation by its shell and the earth above it. It is possible to determine a circular area above the dose point in the shelter which would contribute a certain fraction of the total dose to the point. Supposing that the circular area in the source plane which contributed 99 per cent of the total dose to a particular point within a shelter, was to be determined. It could be described by a central angle, θ, originating at the dose point. This angle would depend on the shelter geometry, the depth of cover, the characteristics of the soil, and the energy and character of the nuclear radiation being considered.

Since a shelter does not consist of a single point, the entire area must be considered. If we were still interested in determining those areas which contributed 99 per cent of the dose to any point within a shelter, we could combine the circular patterns for individual points until every point within the shelter was covered. In so doing, we would describe an area in the source plane which would have the same configuration as the floor of the shelter itself. This area in the source plane and the volume of soil below it can be described as the "critical shielding volume" since it is this volume of soil which provides the bulk of the shielding to the shelter itself.

If this wedge of soil is left undisturbed by conduits or entrances then the shelter-shield system will approach the ideal; i.e., one which does not have any openings at all. Since entranceways and ducts must penetrate the shield to gain access to the shelter space, it would be desirable to locate these openings so that damage to the shield will be minimized.

A note of caution is advisable here. Regardless of where a duct, an entranceway, or other opening to a shelter is placed, due regard must be taken to design it so that it will provide the proper amount of radiation protection. This is true of a duct which runs through the critical shielding volume as well as one placed outside this volume. The main difference in such a case, is that the earth-shield-system itself must be reanalyzed if a duct is placed within it since the shielding properties have been changed. If a duct is placed outside of the wedge, only the attenuation properties of the duct itself need be considered.

The object, then, of this study is to determine critical shielding volumes for likely shelter shapes by determining the critical angles which described these volumes, as indicated in Figure 1. Once having determined the critical angle, θ, and the soil volume it limits, the shelter designer can place his conduits, ducts, and entrances so that this volume remains intact.

ANALYSIS

Dose to A Point in A Semi-Infinite Medium.

Before making an analysis of likely shelter shapes, an analysis of the dose rate to a point in a semi-infinite medium should be made. Figure 2 illustrates the physical aspects of the problem. The source is a

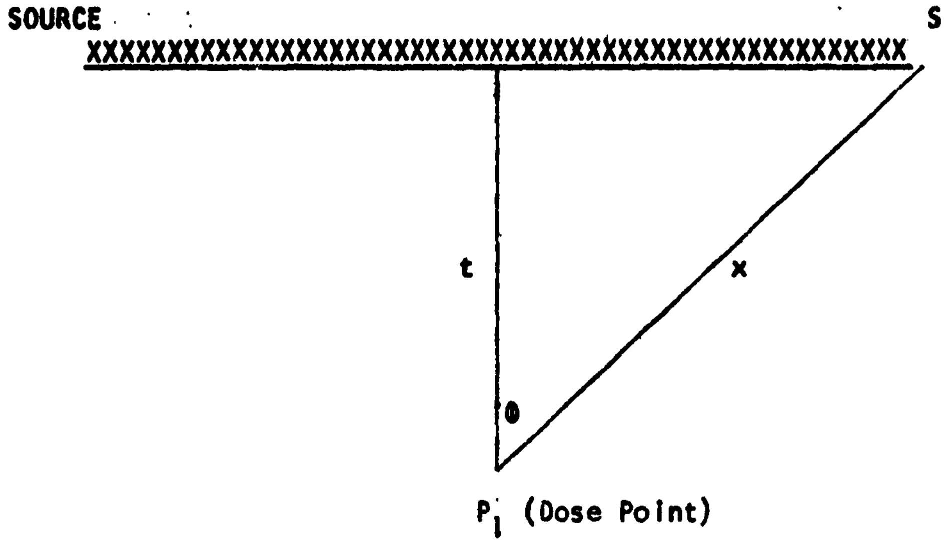


Figure 2. Geometry for the Dose to a Point in a Semi-Infinite Medium.

plane isotropic source on the surface of the semi-infinite medium. The dose rate to point P_1 from the source S_1 is:

$$D_1 = \frac{S_1 f}{4\pi x^2} B_r e^{-\mu x} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where S_1 is the source, photons/sec

f is a conversion factor, r/hr per photons/sec-cm^2

B_r is the buildup factor for scattered radiation

μ is the linear absorption coefficient, cm^{-1}, for the material of the semi-infinite medium

x is the distance from source to detector

The total dose rate from the entire infinite plane source will be:

$$D_\infty = \frac{Sf}{2} \int_t^\infty B_r e^{-\mu x} \frac{dx}{x} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where S is the average source intensity, photons/sec-cm^2

t is the minimum distance from the dose point to the source plane, cm

The buildup factor can be approximated by various mathematical functions. One which has been used quite frequently is:[6]

$$B_r = Ae^{-\alpha_1 \mu x} + A'e^{-\alpha_2 \mu x} \quad \text{.............................. (3)}$$

where A, α_1, and α_2, are constants for a particular photon energy and shield material. $A' = (1-A)$

Using this buildup factor, the integration of Equation 2 can now be performed.

LET:

$$\mu_1 = (\alpha_1 + 1)\mu$$

$$\mu_2 = (\alpha_2 + 1)\mu$$

THEN: $$D_\infty = \frac{Sf}{2}\left[A\,E_1(\mu_1 t) + A'E_1(\mu_2 t) \right] \quad \text{.................... (4)}$$

where E_1 is the exponential integral

The total dose rate from a finite disc centered over the dose point would be:

$$D_\theta = \frac{Sf}{2}\left[AE_1(\mu_1 t) + A'E_1(\mu_2 t) - AE_1(\mu_1 t \sec\theta) - A'E_1(\mu_2 t \sec\theta)\right] \quad (5)$$

where θ is the central angle of the cone which defines the finite area (See Figure 2)

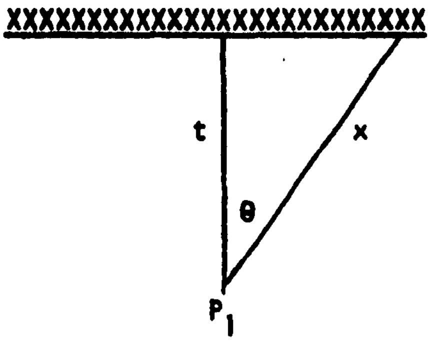
If F is a specific fraction of the total dose, then θ can be determined from the following equation:

$$F\,D_\infty = D_\theta \quad \text{.................................... (6)}$$

Dose to A Point Within A Shelter Cavity.

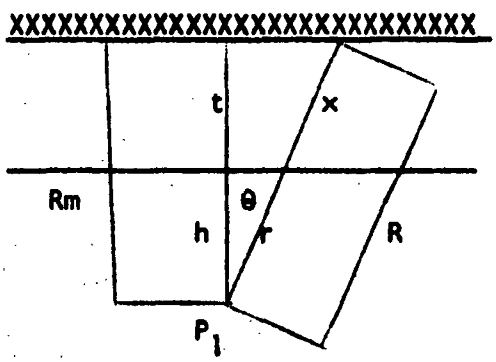
Since we are interested in the dose within a shelter itself, the dose at a point within a semi-infinite medium is an academic problem. Only geometries which are symmetrical about the vertical axis lend themselves to a mathematical treatment. Shelters with a slab shield and a hemisphere configurations are symmetrical about the vertical axis and these will be treated. A comparison of the semi-infinite case to the slab and hemisphere geometries is shown below.

1. Semi-Infinite Medium



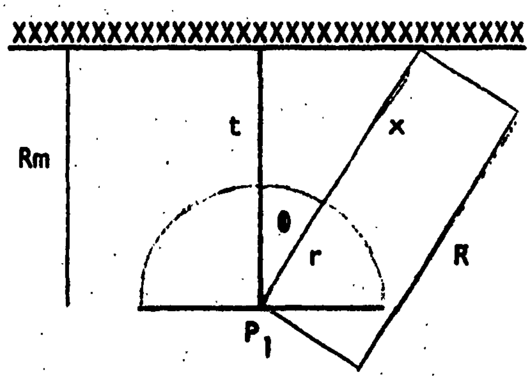
$$D = \frac{Sf}{2} \int_{t}^{\infty} B_r e^{-\mu x} \frac{dx}{x} \quad \text{............} \quad (2)$$

2. Slab Geometry



$$D = \frac{Sf}{2} \int_{t+h}^{\infty} B_r e^{-\mu_a r - \mu x} \frac{dR}{R} \quad \text{......} \quad (7)$$

3. Hemispherical Geometry



$$D = \frac{Sf}{2} \int_{t+r}^{\infty} B_r e^{-\mu_a r - \mu x} \frac{dR}{R} \quad \text{.......} \quad (8)$$

Where μ_a is the absorption coefficient for air

h is the height of the slab shelter roof

r is the radius of the hemisphere

t is the minimum distance of soil shield between source and detector.

Using the same expression for the buildup factor as before, the integration of these equations becomes:

FOR SLAB:

$$D_\infty = \frac{Sf}{2}\left[A\ E_1(\mu_1 t + \mu_a h) + A'\ E_1(\mu_1 t + \mu_a h)\right] \quad \ldots\ldots\ldots\ldots (9)$$

FOR HEMISPHERE:

$$D_\infty = \frac{Sf}{2}\left[Ae^{(\mu_1 - \mu_a)r}\ E_1(\mu_1 R_m) + A' e^{(\mu_2 - \mu_a)r}\ E_1(\mu_2 R_m)\right] \quad \ldots\ldots\ldots (10)$$

Where: $R_m = t + r$

For personnel shelters, the ceiling heights will probably be between 8 feet and 15 feet. The term $\mu_a h_m$ and $\mu_a r$ will be very small in comparison to the attenuation through earth or concrete. Calculations show that they contribute only about one per cent; consequently they will be neglected. The total dose rates, then for a finite portion of the source plane will be:

FOR SLAB:

$$D_\theta = \frac{Sf}{2}\left[A\ E_1(\mu_1 t) + A' E_1(\mu_2 t) - A\ E_1(\mu_1 t \sec\theta) - A' E_1(\mu_2 t \sec\theta)\right] \ldots (11)$$

FOR HEMISPHERE:

$$D_\theta = \frac{Sf}{2}\left[Ae^{\mu_1 r}E_1(\mu_1 R_m) + A' e^{\mu_2 r}\ E_1(\mu_2 R_m) - Ae^{\mu_1 r}\ E_1(\mu_1 R_m \sec\theta) - A' e^{\mu_2 r} E_1(\mu_2 t \sec\theta)\right] (12)$$

Equations for the Solution of θ

Using Equation 6, expressions can be set up to solve for θ. These are:

FOR SLAB:

$$(1-F)\left[(A\ E_1(\mu_1 t) + A' E_1(\mu_2 t)\right] = \left[A\ E_1(\mu_1 t\sec\theta)\ A' E_1(\mu_2 t\sec\theta)\right] \quad \ldots\ldots\ldots (13)$$

FOR HEMISPHERE:

$$(1-F)\left[Ae^{\mu_1 r}E_1(\mu_1 R_m) + A' e^{\mu_2 r}E_1(\mu_2 R_m)\right] = Ae^{\mu_1 r}E_1(\mu_1 R_m \sec\theta) + A' e^{\mu_2 r}E_1(\mu_2 R_m \sec\theta) \quad \ldots (14)$$

Simplified Method

These equations are transcendental expressions which must be solved by a series of trials to obtain the θ which satisfies the expression. If a simplified expression for the buildup factor is used, the final equation will be easier to solve. Previous work has shown that a simple exponential expression will introduce little error for depths of shielding greater than two mean free paths.[3] This expression is:

$$B_r = B_o e^{mx} \quad \text{.. (15)}$$

For practical shelters, soil depths usually range from two feet to about ten feet. The buildup factor can be represented on a log plot by a straight line that deviates least from the buildup factor curve for each photon energy used.

Using this simplified buildup factor equation, the equations for the solution of θ for the slab and hemispheres are: $(\mu_1 = \mu - m)$

FOR SLAB:

$$(1-F)\ E_1(\mu_1 t) = E_1(\mu_1 t \sec \theta) \quad \text{.......................... (16)}$$

FOR HEMISPHERE:

$$(1-F)\ E_1(\mu_1 R_m) = E_1(\mu_1 R_m \sec \theta\_ \quad \text{.......................... (17)}$$

Comparison of Methods

Before the simplified solution can be used it must be compared with the more exact solution. Table I is a machine computation of Equation 13 (slab case) for various photon energies. Table II lists the values of A, α_1, and α_2 which were used.[5] Table III is a machine computation of the solution of Equations 16 and 17, which have exactly the same form. Since μ and μ_1 are different for the same energy photon (Table IV), a comparison between the two methods must be made on an actual depth of soil or shielding material basis. Table V is a tabulation of the data for 1 mev (million electron volts) gamma radiation for both cases. Table VI is a tabulation of the data for 6 mev gamma radiation for both cases. The values tabulated in Tables V and VI are plotted on Figure 3. For 1 mev photons, the simplified method gives values that are about 1 degree less than those of the more rigorous method. The 6 mev solutions plot along the same curve. Based on this comparison, the simplified method will be used hereafter.

The solution of Equations 16 and 17 for θ have been plotted on Figure 4 for values of $\mu_l x$ from 2 to 50. When slab geometry is used, substitute t(depth of cover) for x. When hemispherical geometry is used, substitute R_m (radius plus depth of cover) for x.

It is interesting to note that for μt of 20, the A^1 terms of equations 13 and 14 are only 5 per cent of the A terms and therefore for μt of 20 or more the second terms containing the μ_2 term can be neglected. Doing this, equations 13 and 14 reduce to exactly the same form as 16 and 17 except that there is a μ_1 instead of a μ_l. The values of μ_1 and μ_l are very similar for most photon energies.

THE CRITICAL SHIELDING VOLUME

The critical shielding volume for shelters will arbitrarily be defined in this report as that volume of earth, concrete or other shielding material which provides F fraction of the total shielding. Two values of F have been used herein; 0.99 and 0.999. Angles θ corresponding to these values have been calculated and plotted as functions of $\mu_l x$, Figure 4. These values of θ have been calculated for a single point within either a rectangular or hemispherical shelter.

For a rectangular (slab) shelter, the dose received at a point next to a wall is assumed to be 1/2 that received at the center of the shelter. The dose received in a corner is 1/4 that received in the center. This can be proved rather simply by referring to the figure below. The man at the center of the shelter is receiving radiation from the circular pattern depicted. The man at the wall is receiving radiation from only one-half of a similar pattern because the shielding material on the wall side to the source plane provides much more protection than the air on the inboard side. This can be proved

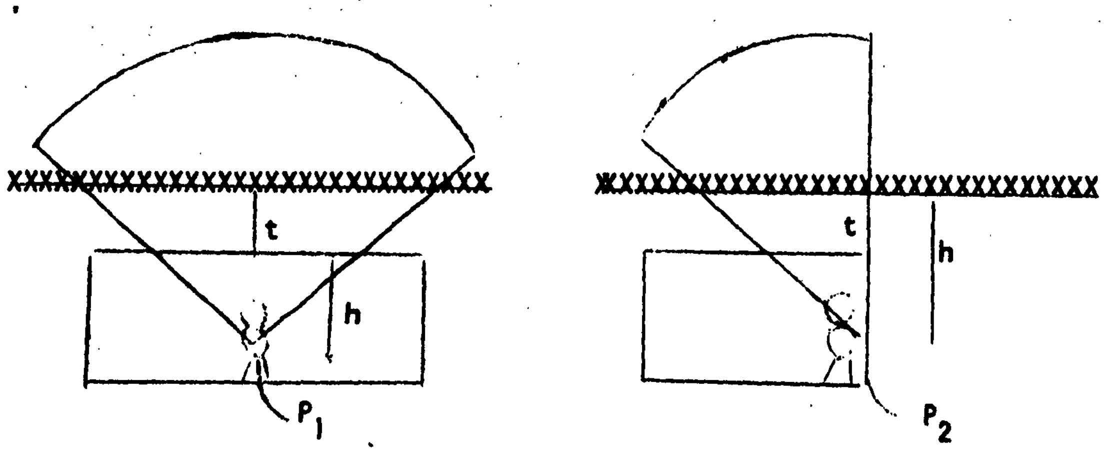


Figure 6

by the following mathmetical exercise:

The dose to point 1 in the above sketch is:

$$D_1 = \frac{SfB_o}{2} E_1(\mu t)$$

The dose to point 2 is:

$$D_2 = \frac{SfB_o}{2}\left[\frac{E_1(\mu t) + E_1(\mu t + \mu h)}{2}\right]$$

Therefore the dose at point 2 relative to point 1 is:

$$\frac{D_2}{D_1} = \frac{1}{2}\left[1 + \frac{E_1(\mu t + \mu h)}{E_1(\mu h)}\right]$$

Since the ratio of $\frac{E_1(\mu t + \mu h)}{E_1(\mu h)} \ll 1, \frac{D_2}{D_1} \cong \frac{1}{2}$

To determine θ then for the position next to the wall the following formula would be used:

$$(1 - 1/2\ F)\ E_1(\mu t) = E_1(\mu t \sec \theta)$$

For practical cases F is usually chosen close to 1.00, therefore:

$$0.5\ E_1(\mu t) = E_1(\mu t \sec \theta) \quad \text{.........................} \quad (18)$$

This curve is plotted on Figure 4.

To determine the critical shielding volume for rectangular shelters the angle for a position next to the wall must be checked against the angle determined for a central position in the shelter. In almost all cases the central angle will govern, and the critical volume of earth will be determined by drawing the angle θ determined with an F of 0.99 or 0.999 from the roof line of the shelter. The angle θ is determined using an F of either 0.99 or 0.999. A check should be made of the wall angle. This should be measured from a position 3 feet from the floor of the shelter, since this is the position at which the dose to a man is usually estimated. The procedure is illustrated in a sample design problem on Page 10.

A spherical shell is much more difficult to analyze than a slab. However an approximation indicates that at the 1/2 radius point the dose is 9/16 of the central dose and at the 1/4 radius point the dose is 0.5007. This is based on conservative assumptions, so that the 0.5 θ curve could be used at the 1/4 radius point for a check on this hemisphere case. In almost all cases, the central angle will govern.

The analysis of the 1/2 and 1/4 radius points is as follows:

As indicated in the sketch below, for the 1/2 and 1/4 points, half of the radiation will come from the inboard side of the shelter and one half from the wall side. The wall side has greater shielding thickness and the dose contribution from the wall will be much less than from the inboard side. A conservative assumption will be made that the contribution from the inboard side is equal to 1/2 of the central dose. The contribution from the wall side can be estimated by assuming that the dose point is located at the center of a smaller sphere whose radius is equal to the distance from the dose point to the surface of the shelter. See Figure 7 below.

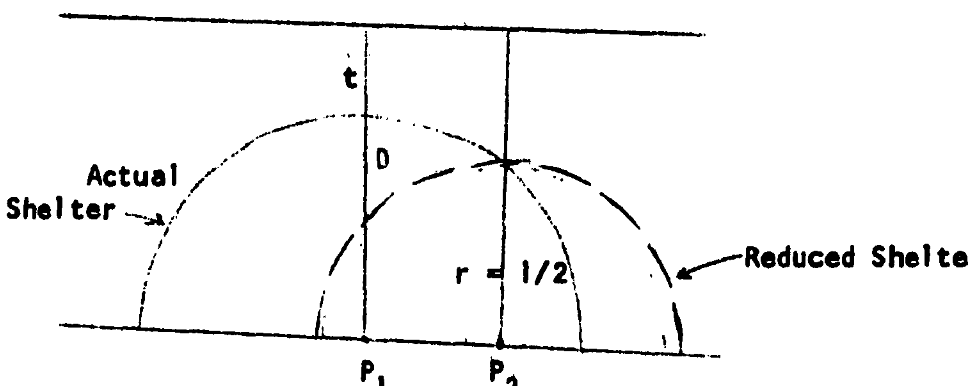


Figure 7

The dose to the central point of a sphere is:

$$D = \frac{SfB_o}{2} e^{\mu r} E_1(\mu R_m)$$

The radius of the reduced sphere for the 1/2 point would be:

$$r_{1/2} = \sqrt{r^2 - r^{2/4}} = 0.866\ r$$

Using the approximation that $E_1(x) \approx \frac{e^{-x}}{x}$, the relative doses would be:

$$\frac{D_2}{D_1} = e^{-\mu r\ (1 - 0.866)}$$

For a μr of 10, this ratio would then be:

$$\frac{D_2}{D_1} \approx \frac{1}{8}$$

The dose at point 2 would then be the average of the inboard and wall-side doses or 9/16 of the central angle dose. A similar procedure obtains the value of 0.5007 for the 1/4 point.

The Determination of Angle θ

The curves presented in Figure 4 give θ as a function of $\mu_i x$. For slab geometry use t for x. For hemispherical geometry use R_m for x. These curves can be used for both initial and residual gamma radiation. Since μ_i is a function of photon energy, a value of μ_i can be determined which corresponds to the average energy of the radiation being considered. For initial radiation, the nitrogen gamma spectrum is the most predominant energy source.[4] The average energy, therefore, for initial gamma radiation should be about 6 or 7 mev. For residual radiation and energy between 0.7 and 1.2 mev is usually used. Once μ_i is determined, the value of $\mu_i t$ or $\mu_i R_m$ can be determined and the angle θ taken from the proper curve. Table IV gives values of μ_i for various photon energies.[3]

The computed angle is then applied to a profile of the structure to determine the critical shielding volume. Ducts and entranceways or other openings to the shelter are then constructed to avoid, as much as possible, violating this volume of cover. Figure 5 is an isometric sketch illustrating this conception.

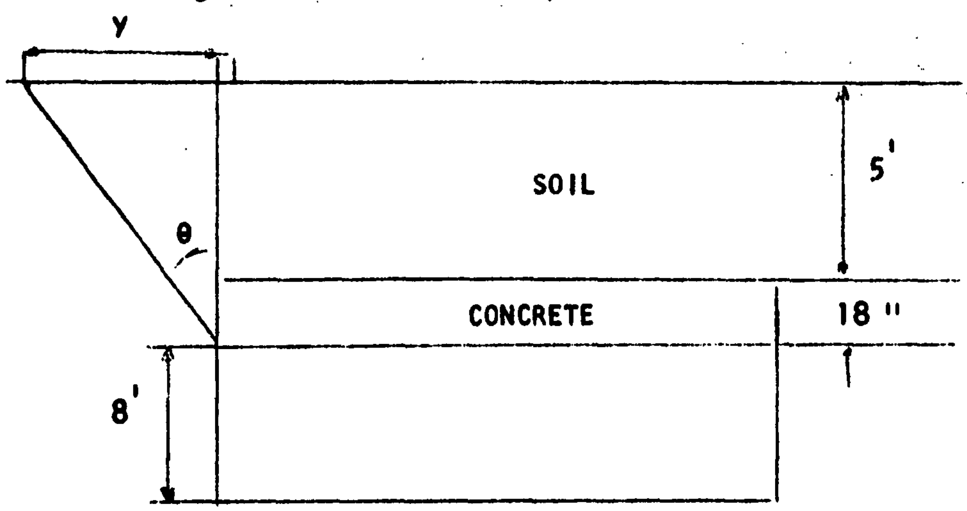
A Design Procedure

The following design problems are presented to illustrate the use of the curves in this study.

1. GIVEN: A concrete rectangular shelter; 25x50x8 with a roof 18 inches thick. The concrete is 144 pounds per cubic feet. To attenuate the initial gamma radiation, requires an additional 5 feet of earth cover, compacted to a density of 119 pounds per cubic feet.

   FIND: The dimensions of the critical shielding wedge.

The following sketch outlines the problem.



The angle θ must be determined from which the dimension y can be calculated. The dimensions then of the critical wedge at the surface of the ground would be: $(25 + 2y)(50 + 2y)$.

Since we are dealing with initial gamma radiation, the value of μt must be determined for the problem. For initial gamma radiation we should use a photon energy of 6 mev. From Table IV a μ of 1.27 ft^{-1} is obtained for an earth density of 1.7 (106 pcf). The μt then would be the sum of the μt for earth cover and the concrete roof.

$$\mu t = 1.27 \times 1.5 \times \frac{144}{106} + 1.27 \times 5 \times \frac{119}{106}$$

$$\mu t = 2.59 + 7.14 = 9.73$$

Entering Figure 4 with this value, we obtain a θ of 46.5°. ($F = 0.99$) and 53° ($F = 0.999$). Since

$$y = t(\text{actual}) \tan\theta$$

$$y\ (F \text{ of } .99) = 6.86 \text{ feet}$$

$$y\ (F \text{ of } .999) = 8.72 \text{ feet}$$

The dimensions of the wedge at the surface of the ground would then be: 38.7 x 63.7 or 42.4 x 67.4 for the two cases.

A check must be made to see whether or not the dose to the side wall of the shelter governs. The θ corresponding to the side wall dose is taken from the $F = 0.5$ curve of Figure 4; for a μt of 9.7, $\theta = 20^\circ$. This angle must be taken from 3 feet above the floor line at the wall. The distance y corresponding to this position would be:

$$y = t' \tan\theta, \text{ where } t' = 6.5' + 5.0', \quad \theta = 20^\circ$$

$y = 4.2'$, this is smaller than either value above, consequently the angle of the wedge can be drawn from the roof line of the shelter.

2. GIVEN: A hemispherical shelter with an internal radius of 10 feet, a concrete shell thickness of 6 inches (144 pcf), and a depth of soil over the crown of 5 feet. The soil is 119 pcf compacted density.

FIND: The radius of the critical shielding volume for an F of 0.99 and 0.999.

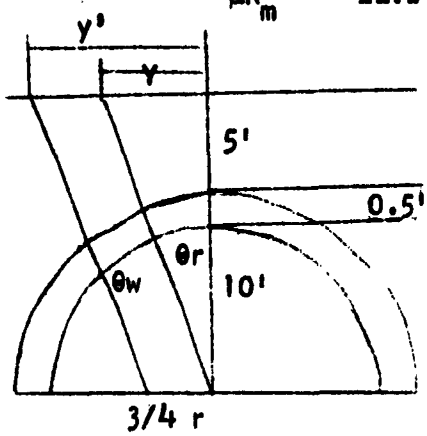
For initial gamma radiation, a photon energy of 6 mev is again used. From Table IV, μ is 1.27 ft^{-1} for 106 pcf soil. From the sketch below we wish to calculate y for F's of 0.99 and 0.999 and a y' for an F of 0.5.

The larger radius will govern. For hemispherical geometry, the μx used to determine the angles θ, is μR_m where R_m is the sum of the radius of the shelter plus the earth cover. The μ, used is calculated for the soil cover, consequently, the concrete arch must be converted to an equivalent thickness of earth. The calculation of μR_m is as follows:

$$\mu t = 5 \times 1.27 \times \frac{119}{106} + 0.5 \times 1.27 \times \frac{144}{106} = 7.984$$

$$\mu r = 10 \times 1.27 \times \frac{119}{106} = 14.22'$$

$$\mu R_m = 22.2$$



From Figure 4 then:

$\theta(0.99) = 33.2^{\circ}$

$\theta(0.999) = 39.5^{\circ}$

$\theta(0.5) = 14^{\circ}$

$y = R_m \tan \theta$

$y' = 7.5 + R_m \tan \theta(0.5)$

Since $R_m = 15.5'$

$y\,(0.99) = 10.1\,'$

$y(0.999) = 12.75\,'$

$y\,(0.5) = 11.37\,'$

Therefore for the 0.99 case we would use a value of 11.37' and for 0.999 case we would use 12.75'.

RECOMMENDATIONS

The following construction principals are recommended to obtain the most effective shield for buried shelters:

(1) To maintain shield integrity; the critical shielding volume should contain no vents, ducts, or openings.

(2) The critical shielding volume should receive the greatest attention in the backfilling operation to insure maximum density of optimum moisture content; since it provides most of the nuclear radiation protection.

(3) For protection against nuclear radiation, the slope of any berm required should be started beyond the confines of the critical shielding volume. It is recognized that the final slope and size of an earth berm may depend upon structural or other functional considerations which may well require it to extend beyond the limits of the critical volume.

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TABLE 1. The Value of the Angle θ as a Function of μt_m for Various Photon Energies for Slab Geometry

Photon Energy Mev	SOIL MEAN FREE PATHS, μt_m						
	2	4	6	8	10	12	14
0.5	72.7	63.0	56.5	51.6	47.9	44.8	42.3
1.0	72.3	62.6	56.0	51.2	47.4	44.4	41.9
2.0	71.8	62.1	55.6	50.7	47.0	44.0	41.5
4.0	71.4	61.7	55.2	50.5	46.8	43.8	41.3
6.0	71.3	61.6	55.2	50.4	46.7	43.8	41.3
8.0	71.1	61.5	55.1	50.3	46.7	43.7	41.3
10.0	71.0	61.4	55.0	50.2	46.6	43.6	41.2

TABLE II Values of A, α_1 and α_2 for Concrete and a Point Isotropic Source

Photon Energy, Mev	A	α_1	α_2
0.5	12.5	0.111	0.01
1.0	9.9	0.088	0.029
2.0	6.3	0.068	0.058
4.0	3.9	0.059	0.078
6.0	3.1	0.0585	0.083
8.0	2.7	0.057	0.0855
10.0	2.6	0.05	0.0835

TABLE III The Value of θ as a Function of $\mu_1 x$ for Slab and Hemispherical Geometry for F Values of 0.99 and 0.999

$\mu_1 x$	θ (F = 0.99)	θ(F = 0.999)
2	69.6	75.1
4	60.0	66.6
6	53.7	60.7
8	49.1	56.2
10	45.6	52.5
12	42.7	49.6
14	40.3	47.0
20	34.9	41.3
25	31.8	37.8
30	29.5	35.1
35	27.5	33.0
40	25.9	31.1
45	24.6	29.6
50	23.4	28.2

TABLE IV Values of $\frac{\mu}{\rho}$, μ, $\frac{\mu_l}{\rho}$, and μ_l for Gamma Photon Energies from 1 to 10 mev

Photon Energy, Mev	$\frac{\mu}{\rho}\ \frac{g}{cm^2}$	$\mu\ ft^{-1}$	$\frac{\mu_l}{\rho}\ \frac{g}{cm^2}$	$\mu_l ft^{-1}$
1.0	.0635	3.28	.058	3.00
2.0	.0445	2.30	.041	2.12
4.0	.0317	1.64	.029	1.50
6.0	.0268	1.28	.0245	1.27
8.0	.0243	1.25	.0217	1.12
10.0	.0229	1.18	.020	1.03

TABLE V Tabulation of Equations 13 and 16 vs Depth in Feet for Slab Shield for 1 mev Gamma Photons

$$\left[\frac{\mu}{\rho} = .0635\ \frac{g}{cm^2},\ \frac{\mu_1}{\rho} = 0.58\ \frac{g}{cm^2}\right]$$

$t_m(ft_1)$	μt_m	$\mu_1 t_m$	θ^o
.61	2		72.7
.67		2	69.6
1.22	4		62.6
1.33		4	60.0
1.83	6		56.0
2.00		6	53.7
2.44	8		51.2
2.67		8	49.1
3.05	10		47.4
3.33		10	45.6
3.66	12		44.4
4.00		12	42.7
4.27	14		41.9
4.67		14	40.3

TABLE VI Tabulation of Equations 13 and 16 vs Depth in Feet for Slab Shield for 6 mev Gamma Photons

$$\left[\frac{\mu}{\rho} = .0268\ \frac{g}{cm^2}, \quad \frac{\mu_1}{\rho} = .0245\ \frac{g}{cm^2}\right]$$

$t_m(ft_1)$	μt_m	$\mu_1 t_m$	θ^o
1.45	2		71.3
1.58		2	69.6
2.90	4		61.6
3.15		4	60.0
4.35	6		55.2
4.73		6	53.7
5.8	8		50.4
6.32		8	49.1
7.25	10		46.7
7.87		10	45.6
8.70	12		43.8
9.45		12	42.7
10.15	14		41.3
11.05		14	40.3

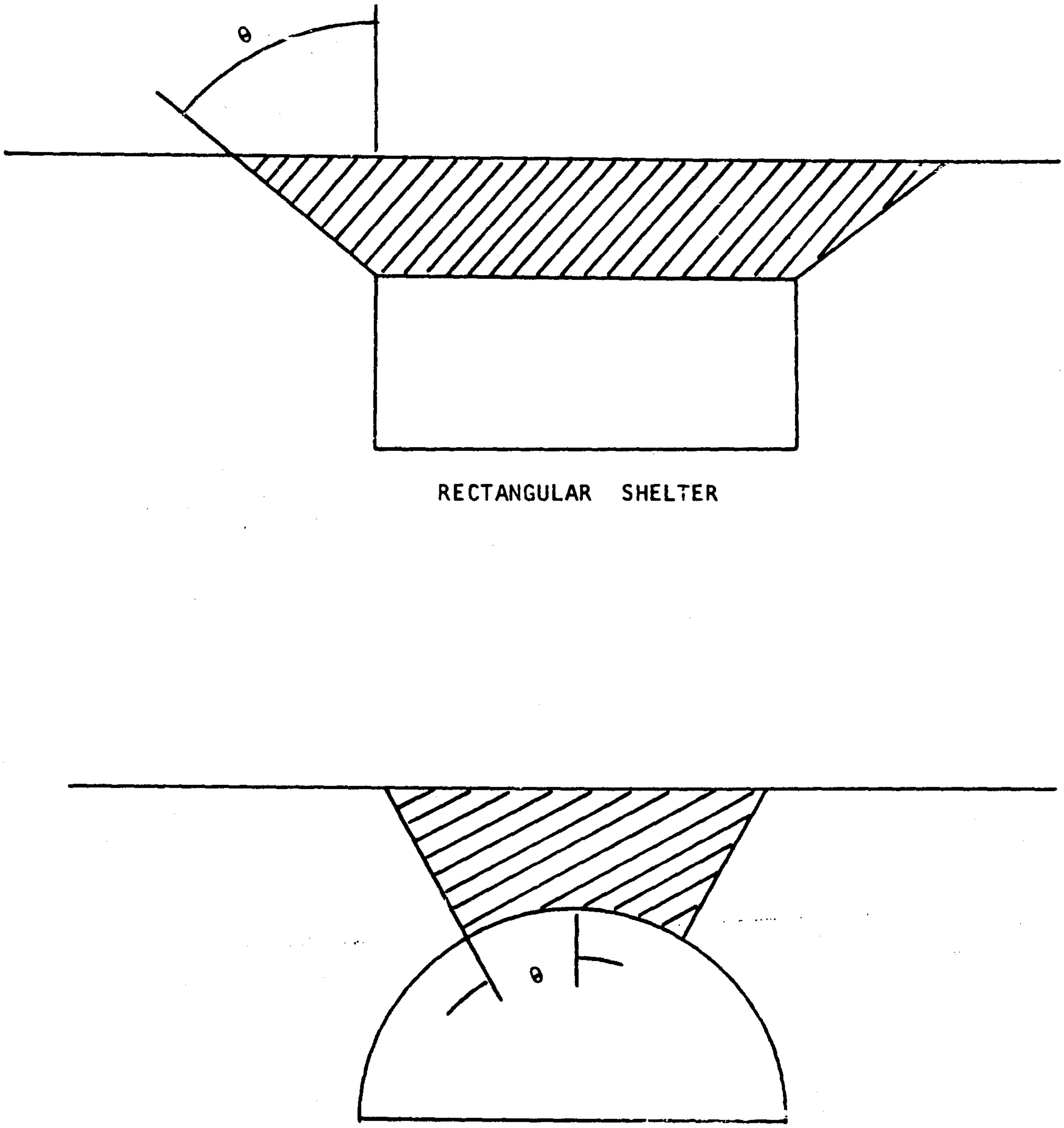

Figure 1. Critical shielding volume for rectangular and hemispherical shelters.

FIG. 2

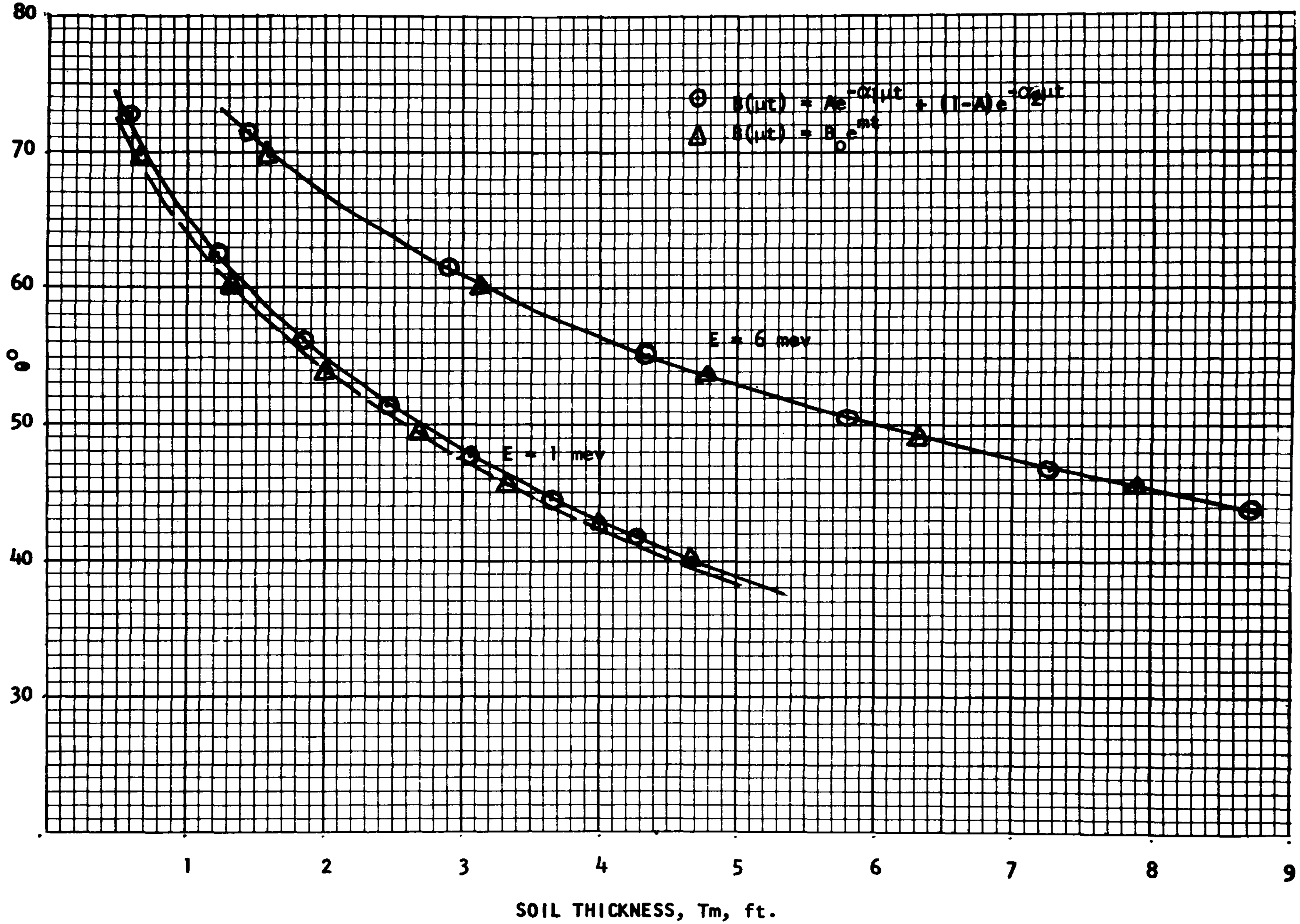

Figure 3. Solution of the angle θ using two different build-up factor formulas.

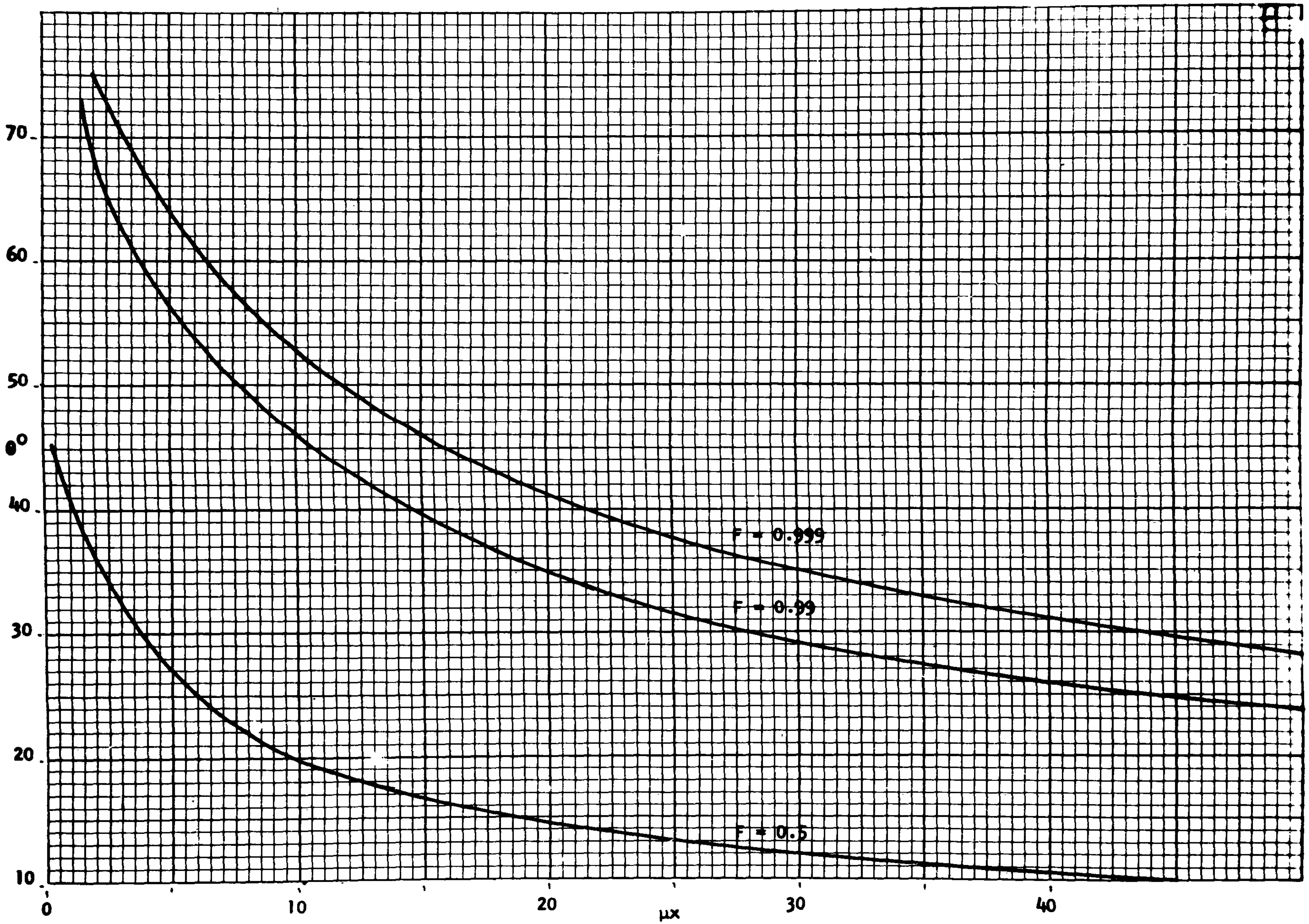

Figure 4. Solution of the equation: $(1-F)\,E_1(\mu x) = E_1(\mu x \sec\ \ )$ for various values of F.

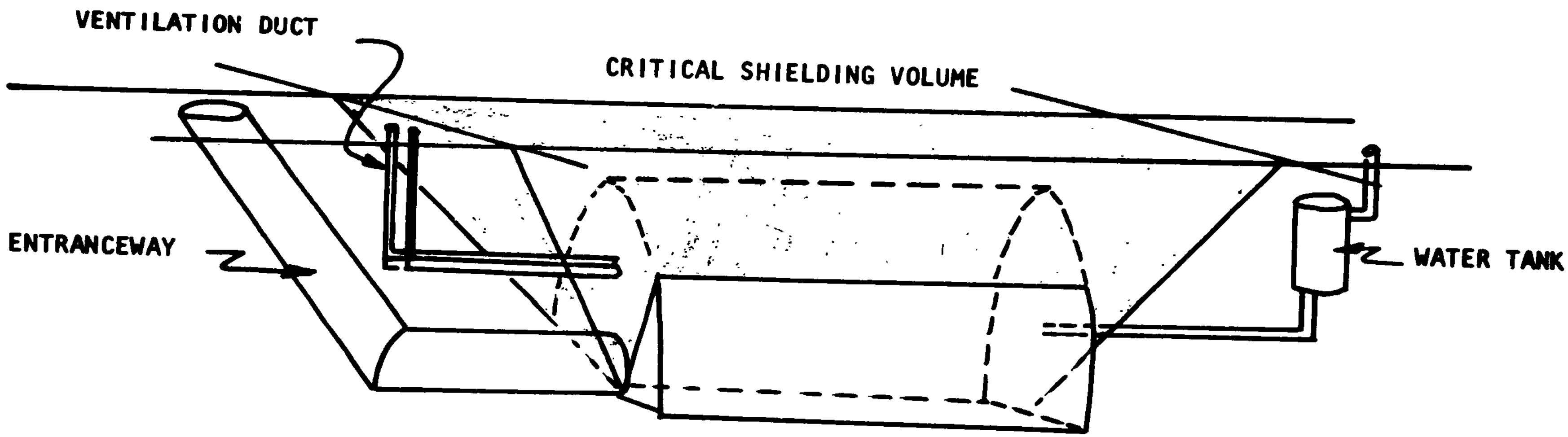

Figure 5. Buried shelter indicating the critical shielding volume and the placement of entranceway and utility ducts.